Available online at www.sciencedirect.com

SciVerse ScienceDirect

Physics Procedia 41 (2013) 603 – 609

Physics Procedia

Lasers in Manufacturing Conference 2013

Dicing of thin Si wafers with a picosecond laser ablation process

C. Fornaroli*, J. Holtkamp, A. Gillner

Fraunhofer ILT, Steinbachstraße 15, 52072 Aachen

Abstract

These days most common way to produce electrical components like LEDs, solar cells or transistors is a batch process. Therefore a lot of identical components are processed parallel on one big wafer and eventually each chip has to be singulated. Currently two dicing technologies have established themselves, which can be devided in mechanical blade sawing and laser based processes with nanosecond lasers. In contrast to these technologies, laser dicing with picosecond lasers offers fundamental advantages like smaller kerf width and marginal heat effected zones. In this paper the cutting process of Si wafers with ps lasers is investigated with regard to optimized process parameters like pulse energy, polarization and overlap.

Keywords: Cutting; Dicing; Singulation; Si Wafer, picosecond Laser, UKP,

1. Motivation / State of the Art

Mechanical sawing with diamond blades have been used for a long time but as the wafer material is getting thinner and the chip size smaller, this classical process is replaced by laser based dicing processes. Especially the mechanical load and the relatively large kerf width are serious disadvantages of a mechanical dicing process. A reduction of the kerf width leads to a much higher yield.of chips per wafer and therefore to an increase in efficiency and resource conservation at the same time. Furthermore diamond blades are basically not suitable to cut thin wafers in the range of 100 µm or less, because they cannot resharpen themselves at the thin wafer edge.

Thus several laser dicing technologies are currently available on the market:

- Full cut with ns laser at UV-Wavelength [1]
- Stealth dicing with ns at IR-Wavelength [2]
- Full cut with a water-jet guided ns laser at IR-Wavelength [3]

Although these developed technologies overcome some of the problems connected with a mechanical

* Corresponding author. Tel.: +492418906642
E-mail address: christian.fornaroli@ilt.fraunhofer.de

doi:10.1016/j.phpro.2013.03.122

sawing process, there is still a lot of optimization potential. For example the kerf loss in a ns laser cutting process is still in the range of 50 µm. Stealth dicing has shown great potential, but gets problems if metallic layers on the wafer surface occur. In a water-jet guided laser cutting process it could be rather difficult not to damage the polymer tape, which is typically sticking below the wafer. Taking all this into account it is worth to investigate the suitability of a picosecond laser ablation process for the dicing of thin Si wafers. However the process parameters are not completely known and so the goal of this paper is to investigate the cutting process of Si wafers with picosecond laser sources with regards to optimized process parameters like pulse energy, wavelength, spot diameter, polarization and overlap.

2. Experimental

The experiments are carried out with a Lumera HyperRapid 50 with a wavelength of λ = 532 nm, an average Power of 22 W @ 400 kHz and pulse duration of τ <15 ps. The laser beam is deflected by a Scanlab IntelliScan 14DE Galvo scanner and focussed by a 100mm f-Theta lense to a spot diameter of 14 µm. The laser source and the whole beam path are included in a Kugler MICROGANTRY Nano3x with aerodynamic bearings for highest precision, Fig. 1.

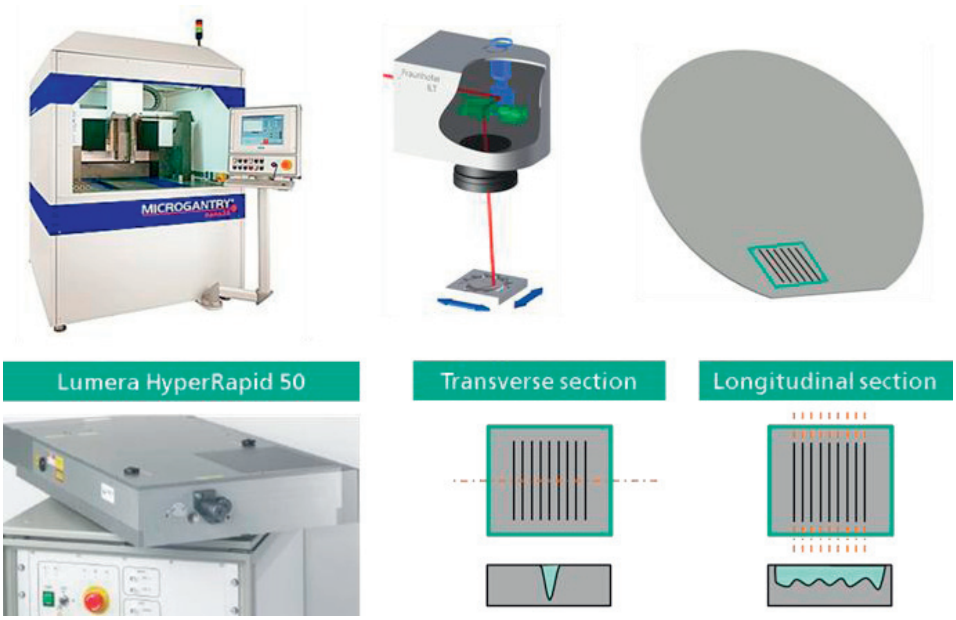

Fig. 1. Experimental setup and approach

In contrast to the thin wafers, which are in the focus of the process development, the fundamental ablation experiments are carried out with 500 µm thick boron doped silicon wafers. This wafer thickness is much easier to handle and furthermore it possible to break the material in and perpendicular to the cutting direction with a result of clean break lines without cracks. The comparability of both material thicknesses has been already investigated and is in the range of a few micrometers. The transverse section is suitable to review the depth profile of the ablated groove and sticking debris at the edges. In preliminary experiments it has been observed that the cutting depth is not constant along the cutting direction, but rather varying. Closer examinations of the longitudinal section can reveal such an uneven structure. The sections are investigated and documented with a digital light microscope from Keyence, a laser scanning microscope (LSM) and partially with a scanning electron microscope (SEM).

Fig. 2 shows the beam profile of the used laser source, a Lumera HyperRapid 50. The Beam quality is better than $M^2 = 1.5$ and the Rayleigh length is 280 µm. The raw beam diameter is expanded with a telescope from 2.5 mm to 5 mm and afterwards focussed with a 100 mm F-Theta focussing optics. The Gaussian diameter of the focussed beam amounts to $2\omega_0 = 14\ \mu m$ at the Intensity level of $1/e^2$. 100 µm beyond and below the focal plane the beam shape is elliptical and also a slightly astigmatism can be observed.

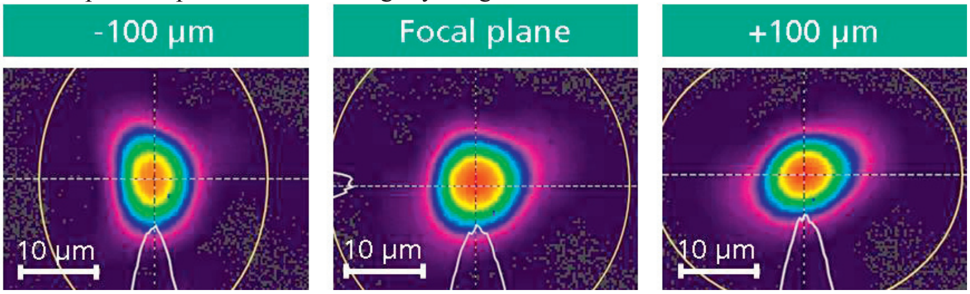

Fig. 2. Beam profile in the focal plane and near the focal plane

During the experiments the following parameters are varied in order to determine the best combination for clean and efficient cutting of the silicon wafer:

- Pulse energy near the ablation threshold and many times higher
- Scanning speed up to several meters per second
- Temporal spot Overlap from 50% to 99%
- Number of repeats

With respect to the literature and the basic ablation theory of ultra-short pulsed lasers, the best ablation results are to be expected at a very low fluence near the ablation threshold of the material. Thus first of all this threshold is determined with the method provided by J. M. Liu [4]. In this method the radius of a single pulse ablation is measured while the pulse energy is varied. Eventually this measured radius is squared and plotted over the logarithm of the fluence. The ablation threshold can be determined to 0.15 J/cm² for a wavelength of 532 nm, which matches quite good with values from the literature. In combination with a spot diameter of $2\omega_0 = 14$ µm follows a pulse energy $E_p = 0{,}23$ µJ.

3. Results and Discussion

First of all the ablation process at a low fluence level is investigated. The pulse energy is set to 1 µJ which implicates a fluence of 0,65 J/cm² (4 times more than the ablation threshold). At a repetition rate of 400 kHz two temporal pulse overlaps are adjusted with feed rates of 1500 mm/s to 70% and 50 mm/s to 99 %. Thus a potentially thermal effect can be identified by changes in the ablation depth or a larger heat affected zone. In any case the impact of a higher amount of pulses shows up, because at 99 % pulse overlap 30x more pulses are hitting the kerf. Fig. 3 shows ablation graphs for the kerf width and depth for both pulse overlaps. The orange diamonds indicate a pulse overlap of 70 %, while the blue squares show the development of the cutting geometry at 99 %. The development of the groove depth is nearly the same for both settings and digressive proportional to the number of repeats. Although the cutting depth for 99 % is growing more steeply and amounts already 28 µm in contrast to 19 µm for 70 % after 250 repeats, the gap between both curves shrinks with a growing number of repeats. Finally the difference in cutting depth between both parameters is only 2 µm. The kerf width is nearly constant and invariant to the number of repeats for both pulse overlaps. At 70 % overlap the width is 17 µm and grows to 20 µm at 99 %.

In general it is shown that a sufficient cutting depth of 120 µm attainable with a fluence of 0,65 J/cm². Even a very high overlap of 99 % and thus 30x more pulses does not obtain an improvement. Because of the digressive development it is also not possible to get much deeper with an increased number of repeats. For example the cutting depth is 34 µm after 1000 and 38 µm for 2000 repeats. An extrapolation of this values leads to a depth of 40 µm after 3000 runs and afterwards the depth is only growing on nanometer scale. This kind of development is quite comprehensible, when the microscope pictures from the bottom of Fig. 3 are taken into account. At the beginning of the ablation process the incident laser radiation is absorbed at the material surface with an angle 0° and the groove is formed. The deepest point is to be found at the center, resulting from the highest intensity of the Gaussian beam profile. During the next ablation steps the incidence angle of the arriving beam is not constant anymore within the groove. At the center position it is still vertically, but at the left and right side an angle emerges. The beam profile is projected on this angular surface, the effective beam diameter increases and eventually the fluence decreases if the pulse energy is constant. This process reinforces itself because of the combination of a Gaussian beam profile and the angled surface. When the angle of the wall reaches a critical value, the projected intensity falls below the ablation threshold and explains the stop of the ablation and the asymptotic contour.

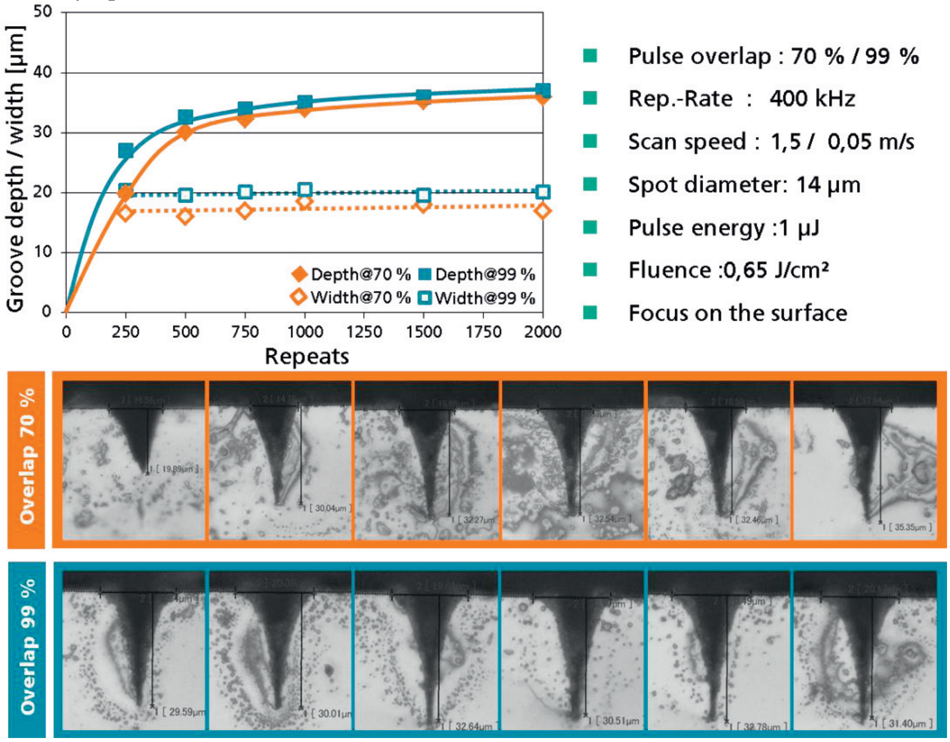

Fig. 3. Groove geometry at a fluence of 0,65 J/cm² at two different pulse overlaps with varying number of repeats

As shown in the previous section a fluence of 0,65 J/cm² is obviously not sufficient to reach the desired cutting depth of 120 µm, although this amount is already 4 times more than the ablation threshold. Thus also higher fluence levels up to 4,8 J/cm² are investigated in terms of the attainable cutting depth. At a repetition rate of 400 kHz the scanning speed is set to 2500 mm/s, which means a temporal pulse overlap of 50 %. The spot diameter is still 14 µm and the focal plane is adjusted to the material surface. Fig. 4 shows ablation results for 2,5, 5 and 7,5 µJ pulse energy for up to 1000 repeats. The development of groove depth and width are very similar to already mentioned shape at 1 µJ, but the attained cutting depth is much bigger. At 2,5 µJ pulse energy the turning point is at about 250 repeats and a depth of 37 µm. After 1000 repeats a final groove depth of 50 µm can be measured. With the doubled fluence a depth of 90 µm and with tripled fluence 115 µm are attained. Hence an increasement of the pulse energy does not lead to a linear proportional change in the ablation rate, but rather to a logarithmic increasement because of saturation effects.

In analogy to the previous diagram the groove width is again invariant regarding the number of repeats. At 2,5 µJ the width is 22 µm, at 5 µJ 31 µm and at 7,5 µJ the width amounts 37 µm at the entrance of the kerf. This leads to the assumption that the kerf width is completely independent from process parameters like overlap or number of repeats and only depending on the fluence level in proportion to the ablation threshold, the effective laser diameter. In Addition the cutting depth is obviously also only affected by the incident laser fluence. If the critical laser fluence exceeded, enough energy reaches the ground of the kerf. Unfortunately groove depth and width are working in opposite directions, because on the one hand very narrow geometries are demanded but on the other hand the material thickness of 120 µm has to be cut through. Thus a trade-off between in terms of the pulse energy is required.

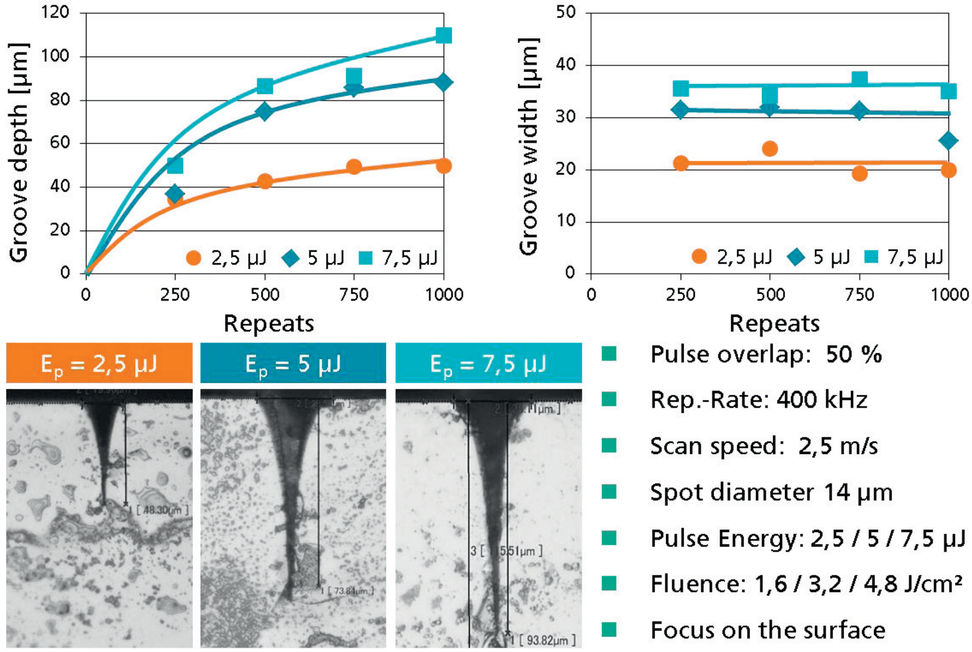

Fig. 4. Groove geometry at higher fluence levels with varying number of repeats

So far the experimental results were only analysed regarding the profile quality. Another very important issue is the process speed. For the example shown in Fig. 4 the scanning speed amounts 2500 mm/s and at 7,5 µJ round about 1000 repeats are necessary to reach the desired cutting depth. This implicates an effective cutting speed of 2,5 mm/s. Currently industrial dicing speeds are in the range of 100 mm/s for thin silicon wafers. But there is some optimization potential left, for instance beam parallelization, higher scanning speeds at higher repetition rates or improved and Taylor beam properties.

Besides the transverse section, which only contains the depth information in one discrete plane, the longitudinal section provides information about the cutting structure in feed direction. Fig. 5 shows light microscope pictures and SEM recordings from longitudinal cuts. The groove geometry results from experimental parameters similar to Fig. 3. The pulse energy amounts 1 µJ, while the pulse overlap is 70 %. The finally reached cutting depth is 38 µm. The upper part of Fig. 5 shows the development of the structure in scanning direction and furthermore the depth. A very rough structure with deep pits can be observed after 250 repeats and remains until 1000 repeats. Up to 750 repeats these pits cause depth differences in the range of 5 µm. Afterwards the pits are even starting point for micro cracks. The SEM pictures in the lower part of the figure show this structure in detail. The structure seems to be periodic and shows similarity to cone-like protrusions, which are known from metal ablation with ultra-short pulsed lasers. The development of this topography during the cutting process is until now without explanation and needs further attention in the upcoming experiments. For the final dicing process these pits could lead to significant damage of the polymer tape beyond the wafer.

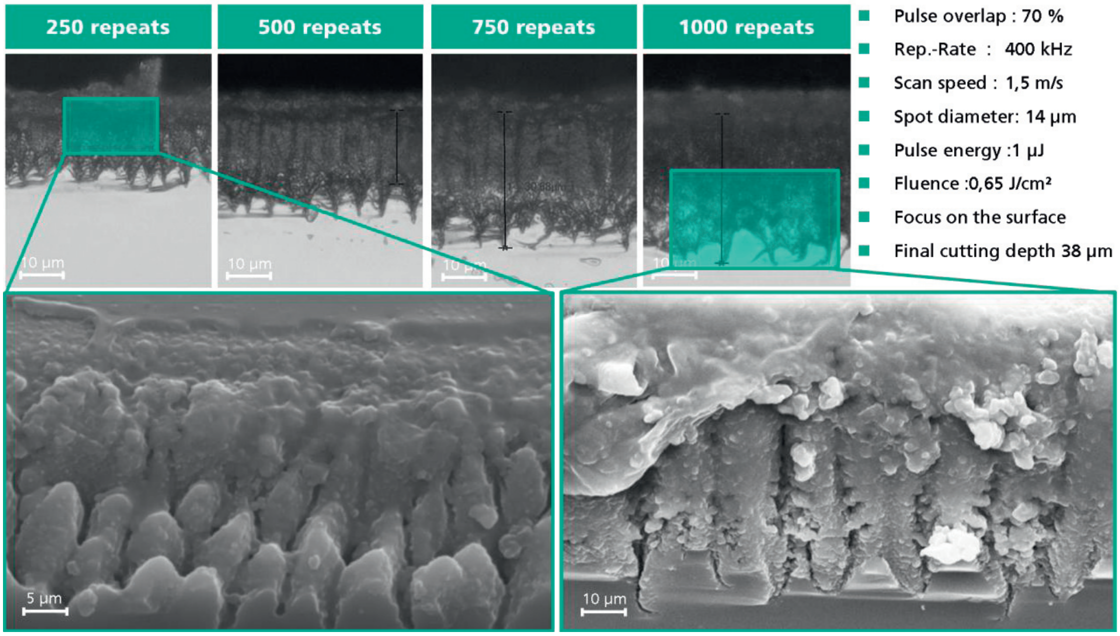

Fig. 5. Microscope and SEM-pictures of the longitudinal section

4. Summary

Dicing of thin silicon wafers with an ultra-short pulsed laser system is investigated in terms of attainable cutting depth together with as small as possible kerf width. The experiments are carried out using a frequency doubled Lumera HyperRapid ps-Laser with a wavelength of 532 nm. A spot size of 14 µm is attained by using a 100 mm f-Theta lense together with 2x beam expander. The experiments show a strong correlation between the maximum cutting depth, groove width and the adjusted laser fluence. The groove geometry is independent from the varied process parameters and results directly from the Gaussian intensity distribution of the incident laser beam. Thus the largest amount of material is always removed in the center of the cutting kerf, because of the peak intensity. Around the center a smaller intensity leads first to angled wall, second to insufficient laser fluence and finally to an ablation stop if the ablation threshold is not reached anymore. Unfortunately cutting depth and groove width are working in opposite direction and so a trade-off has to be found. The process speed is currently not high enough, but can be easily increased by beam parallelization respectively faster scanning speeds.

References

[1] Bovatsek J M, Patel R S. Highest-speed dicing of thin silicon wafers with nanosecond-pulse 355nm q-switched laser source using line-focus fluence optimization technique. Proc. SPIE 7585. Santa Clara, CA. 2010

[2] Masayoshi K, Naoki U, Etusji O, Ryuji S, Kazuhiro A, and Kenshi F. Advanced Dicing Technology for Semiconductor Wafer - Stealth Dicing. Semiconductor Manufacturing, VOL. 20, NO. 3, Taiwan. 2007

[3] Richerzhagen B, Industrial applications of the water-jet guided laser. The Industrial Laser User, Issue 28, Switzerland. 2003

[4] Liu J M. Simple technique for measurements of pulsed Gaussian-beam spot sizes. Optics Letters, Vol. 7, Nr. 5, 1982